Scientia Iranica D (2013) 20 (3), 778–785

SCIENTIA IRANICA

Sharif University of Technology

Scientia Iranica

Transactions D: Computer Science & Engineering and Electrical Engineering

www.sciencedirect.com

Contingency-based optimal placement of Optimal Unified Power Flow Controller (OUPFC) in electrical energy transmission systems

A. Lashkar Ara [a,*], **J. Aghaei** [b], **M. Alaleh** [a], **H. Barati** [a]

[a] *Department of Electrical Engineering, Islamic Azad University, Dezful Branch, Dezful, P.O. Box: 313, Iran*

[b] *Department of Electrical and Electronics Engineering, Shiraz University of Technology, Shiraz, P.O. Box: 71555-313, Iran*

Received 21 June 2012; accepted 12 November 2012

KEYWORDS

FACTS;
OUPFC;
UPFC;
Optimal location;
Contingency analysis;
Energy management.

Abstract This paper presents a new approach to determine the optimal location of an Optimal Unified Power Flow Controller (OUPFC) as an energy flow controller, under a single line contingency (N − 1 contingency), to satisfy operational decisions. A contingency analysis is performed to detect and rank the faulted contingencies on the basis of their severity in electrical energy transmission systems. Minimization of the average loadability on all energy transmission lines is considered as the optimization objective function, while the network settings are set to minimize active power losses under pre-contingency conditions. The optimization problem is modeled using a Non-Linear Programming (NLP) framework and solved using the CONOPT solver. The proposed algorithm is implemented in MATLAB and GAMS software on the IEEE 14- and 30-bus test systems. The simulation results demonstrate the effectiveness of the proposed algorithm in enhancing energy system security under a single line contingency. Furthermore, the OUPFC is outperformed by a Unified Power Flow Controller (UPFC) in normal and contingency operations of electrical energy transmission systems, from technical and economical points of view.

1. Introduction

The reliable and secure operation of power systems is an important task for operators to supply the electrical energy demand under normal and contingency conditions. This is ensured by utilizing Flexible AC Transmission System (FACTS) controllers for some operating conditions. Many FACTS controllers have been proposed and implemented to control the power system under normal states, as well as under contingency conditions. One of the most brilliant of these energy flow controllers in helping to operate the power system reliably and securely is the Unified Power Flow Controller (UPFC) proposed by Gyugyi in 1991 [1]. The other most significant energy flow controller to improve the power system operation technically and economically is the Optimal Unified Power Flow Controller (OUPFC), which is composed of a conventional Phase Shifting Transformer (PST) and a UPFC. The steady-state model of OUPFC and its operational characteristics have been introduced in [2].

The power system consists of both normal and abnormal system performances. Complex studies have been carried out on normal and abnormal performances of a power system, and also in the present and future functioning of the electrical energy system. One of the abnormal performances of electrical energy transmission systems refers to the occurrence of contingencies. The contingency analysis is very important when future conditions are uncertain. Thus, contingency-based planning reflects good energy management practices and helps to create more resilient power systems. Also, it tends to reduce costs, improve energy efficiency, and expand the range of possible solutions compared with more rigid planning. Many studies have been considered for realizing how to enhance system security under contingencies. A Linear Programming (LP)-based Optimal Power Flow (OPF) algorithm for corrective FACTS control to relieve overloads and voltage violations and to minimize average loadability on highly loaded

* Corresponding author. Tel.: +98 641 6260051; fax: +98 641 6260890.
E-mail addresses: Lashkarara@iust.ac.ir (A. Lashkar Ara), Aghaei@sutech.ac.ir (J. Aghaei), mohammad_alaleh@yahoo.com (M. Alaleh), barati216@gmail.com (H. Barati).

Peer review under responsibility of Sharif University of Technology.

ELSEVIER Production and hosting by Elsevier

1026-3098 © 2013 Sharif University of Technology. Production and hosting by Elsevier B.V. Open access under CC BY-NC-ND license.
http://dx.doi.org/10.1016/j.scient.2013.04.007

energy transmission lines is used in [3]. In [4], Particle Swarm Optimization (PSO) and genetic algorithms are used to find optimal location and parameter settings of the TCSC under an N − 1 contingency, and the results of the two ways are compared. An approach for selection of UPFC suitable locations, considering normal and network contingencies, after evaluating the degree of severity of the contingencies, using fuzzy-based composite criteria, is used in [5]. Optimal location and setting of TCSC under a single line contingency, using Mixed Integer Non-Linear Programming (MINLP), are presented in [6]. System static security has been enhanced via optimal placement of TCSC to alleviate overloads during single contingencies in [7]. In [8], the optimal location of STATCOM and SVC, based on contingency voltage stability, has been studied using Continuation Power Flow (CPF).

According to the specification of OUPFC and UPFC, their utilization helps to reduce the power flows of the heavily-loaded energy transmission lines. These energy flow controllers are well capable of providing active and reactive power control [9,10]. Therefore, the main contribution of this paper is to optimally locate OUPFC and UPFC under a single line contingency (N−1 contingency) to implement the contingency-based planning that involves energy management solutions as an alternative to rigid planning. The optimization framework is mathematically modeled as Non-Linear Programming (NLP) and solved using a CONOPT solver in the General Algebraic Modeling System (GAMS) [11], while Matlab is only used to feed parameters to the GAMS routine. The objective function is chosen to minimize the average loadability on all energy transmission lines, and to address dispatcher concerns for operating the power system reliably, securely and economically. The proposed algorithm is tested in IEEE 14- and 30-bus test systems. The simulation results show that OUPFC and UPFC are able to significantly increase system security in N − 1 contingency states, even though UPFC is a more expensive option than OUPFC. Moreover, in some contingencies, these energy flow controllers will prevent network collapse.

The paper is organized as follows. Section 2 explains the model of OUPFC and UPFC based on the power injection model. In Section 3, the problem formulation, including the objective function and constraints for the contingency analysis, is developed. Section 4 contains simulation results followed by conclusions.

2. Modeling of FACTS

In the following, the mathematical modeling of OUPFC and UPFC is presented.

2.1. Modeling of OUPFC

The OUPFC is constructed from a PST and a UPFC linked by two triple winding transformers. The PST, which is connected to secondary windings of exciting and injecting transformers, injects a voltage with a fixed phase to the transmission line controlled by mechanical or static switches. The injected voltage changes the transmission angle, depending on system conditions. The UPFC, connected to a tertiary winding of exciting and injecting transformers, consists of two voltage source converters. The back-to-back converters are operated from a common dc link provided by a dc storage capacitor. The basic schematic of the OUPFC is presented in Figure 1. The

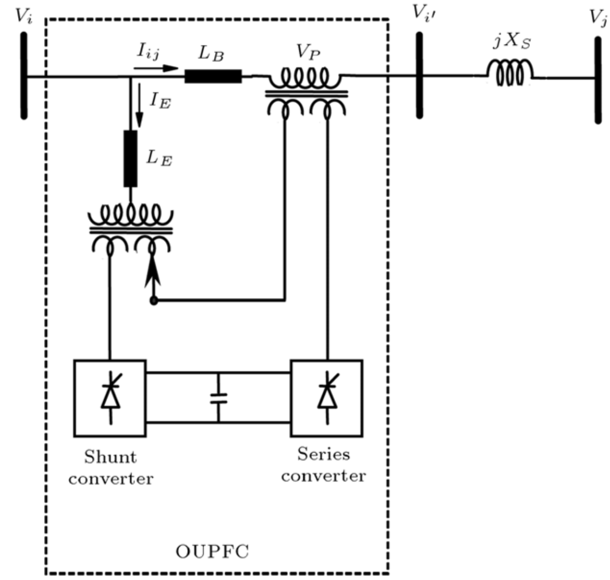

Figure 1: Per-phase schematic diagram of OUPFC.

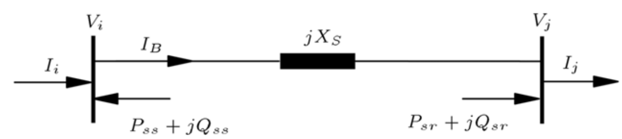

Figure 2: The power injection model of FACTS devices.

power injection model of the OUPFC is shown in Figure 2. Based on this figure, one can reach the following formulations [2]:

$$P_{ss} = -b_s k V_i V_j \sin(\theta_i - \theta_j + \sigma) - b_s r V_i V_j \sin(\theta_i - \theta_j + \gamma), \quad (1)$$

$$\begin{aligned} Q_{ss} = & -b_s V_i^2 (k^2 + r^2) - 2 b_s k r V_i^2 \cos(\sigma - \gamma) - 2 b_s k V_i^2 (\sigma) \\ & - 2 b_s r V_i^2 \cos(\gamma) + b_s k V_i V_j \cos(\theta_i - \theta_j + \sigma) \\ & + b_s r V_i V_j \cos(\theta_i - \theta_j + \gamma), \end{aligned} \quad (2)$$

$$P_{sr} = -P_{ss}, \quad (3)$$

$$Q_{sr} = b_s k V_i V_j \cos(\theta_i - \theta_j + \sigma) + b_s r V_i V_j \cos(\theta_i - \theta_j + \gamma), \quad (4)$$

where r is the radius of the UPFC operating region and γ is the UPFC phase angle [12]. k is the transfer ratio of PST voltage injection, with respect to the exciting transformer, and σ is the PST phase angle [13]. Here, b_s is $1/x_S$. Reactance x_s is the total circuit reactance (the transmission line reactance plus the reactance of the injecting transformer). V_i, θ_i are voltage magnitude and angle of bus i, respectively, and V_j, θ_j are the voltage magnitude and angle of bus j, respectively.

2.2. Modeling of UPFC

The basic schematic of the UPFC is presented in Figure 3. Also, the power injection model of the UPFC is shown in Figure 2. According to the power injection model of UPFC, the following formulation can be extracted [9,14]:

$$P_{ss} = -b_s r V_i V_j \sin(\theta_i - \theta_j + \gamma), \quad (5)$$

$$Q_{ss} = -b_s r V_i^2 (r + 2\cos(\gamma)) + b_s r V_i V_j \cos(\theta_i - \theta_j + \gamma), \quad (6)$$

$$P_{sr} = -P_{ss}, \quad (7)$$

$$Q_{sr} = +b_s r V_i V_j \cos(\theta_i - \theta_j + \gamma). \quad (8)$$

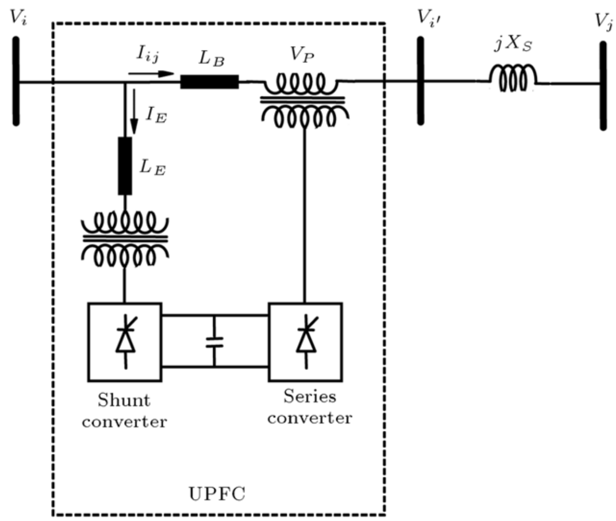

Figure 3: Basic schematic diagram of UPFC.

3. Problem formulation

In this section, the optimization formulations, including objective function and constraints, are discussed.

3.1. Contingency analysis procedure

A contingency is considered to be the outage of power system facilities, e.g., generating units, power transformers or energy transmission lines (branch). A contingency analysis, as one of the responsibilities of power system operators, is performed to establish appropriate preventive and/or corrective actions for each contingency. The purpose of this paper is to focus on single line outage contingencies (N−1 Contingency). For each line outage contingency in the power system, the average loadability on all energy transmission lines is listed. The energy transmission lines are ranked according to the severity of the contingency. Then, the average loadability on all energy transmission lines is obtained with optimal location of FACTS devices to have a variety of flexible and responsive solutions available.

3.2. The objective function

Keeping system security is one of the most important tasks of power system operators under emergency situations. Therefore, the optimization objective is chosen to minimize average loadability on all energy transmission lines, in order to maintain system security, as can be defined as [3]:

$$Z = \frac{1}{nl}\sum_{i=1}^{nl}\frac{S_i}{S_{i,\max}}, \tag{9}$$

where nl is the number of energy transmission lines; S_i is the apparent power flowing through the ith transmission line, and $S_{i,\max}$ is the maximum apparent power flow of the ith transmission line.

Indeed, the apparent power flow of the transmission line includes the apparent power flow from the sending end to the receiving end, and vice versa, named S_{isr} and S_{irs}, respectively. Therefore, the objective function can be rewritten as follows:

$$Z = \frac{1}{2nl}\sum_{i=1}^{nl}\frac{S_{isr}+S_{irs}}{S_{i,\max}}. \tag{10}$$

3.3. Constraints

Optimal Power Flow (OPF) and Power Flow (PF) problems have two sets of constraints, including equality and inequality constraints. These constraints can be described in the following.

3.3.1. Equality constraints

The OPF equality constraints are separated into two sets of active and reactive power balance equations for each bus as follows [15]:

$$P_{Gi} = P_{Di} + \sum_{j=1}^{n} V_iV_jY_{ij}\cos(\alpha_{ij}+\theta_j-\theta_i),$$
$$\forall i \in 1,2,\ldots,n \tag{11}$$

$$Q_{Gi} = Q_{Di} + \sum_{j=1}^{n} V_iV_jY_{ij}\sin(\alpha_{ij}+\theta_j-\theta_i),$$
$$\forall i \in 1,2,\ldots,n \tag{12}$$

where P_{Gi} and Q_{Gi} are the generator real and reactive power at bus-i, respectively, and P_{Di} and Q_{Di} are the load real and reactive power at bus-i, respectively. By adding FACTS devices, the power balance equations will be changed as follows [9]:

$$P_{Gi} + P_{FACTSi} = P_{Di} + \sum_{j=1}^{n} V_iV_jY_{ij}\cos(\alpha_{ij}+\theta_j-\theta_i),$$
$$\forall i \in 1,2,\ldots,n \tag{13}$$

$$Q_{Gi} + Q_{FACTSi} = Q_{Di} + \sum_{j=1}^{n} V_iV_jY_{ij}\sin(\alpha_{ij}+\theta_j-\theta_i)$$
$$\forall i \in 1,2,\ldots,n. \tag{14}$$

3.3.2. Inequality constraints

Inequality constraints in the OPF represent the technical limitation of the active and reactive power generation of units, apparent power flow of energy transmission lines, and voltage magnitude limits of the buses as follows [2,9,16]:

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad \forall i \in NG, \tag{15}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad \forall i \in NG, \tag{16}$$

$$|S_l| \le \left|S_l^{\max}\right| \quad \forall l \in 1,2,\ldots,NL, \tag{17}$$

$$\left|V_i^{\min}\right| \le |V_i| \le \left|V_i^{\max}\right| \quad \forall i \in n, \tag{18}$$

where NG is the number of generators; NL is the number of energy transmission lines; and n is the number of buses.

In addition to the above-mentioned generation constraints, limits of OUPFC and UPFC parameters are given in the Appendix.

3.4. Installation cost of FACTS

The cost of FACTS installation is calculated by the following mathematical equation:

$$\text{Investment cost} = \frac{C_{FACTS}}{8760\times 5} \quad (\$/h), \tag{19}$$

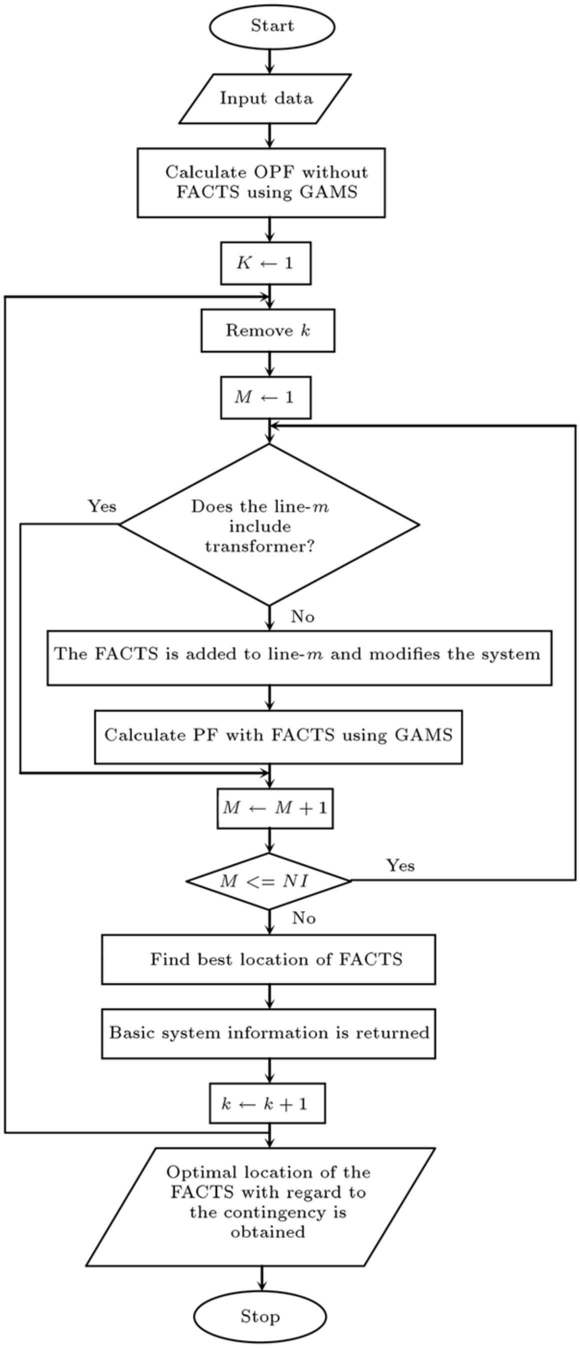

Figure 4: Flowchart of the implemented optimization strategy.

where C_{FACTS} is the cost of FACTS installation in US $. Based on the ABB and Siemens database, the cost functions for PST, UPFC and OUPFC are developed as [9,10,17,18]:

$$C_{UPFC} = (0.0003S_{UPFC}^2 - 0.2691S_{UPFC} + 188.22) \times S_{UPFC} \times 1000, \tag{20}$$

$$C_{OUPFC} = [(12 \times S_{PST}) + ((0.0003S_{UPFC}^2 - 0.2691S_{UPFC} + 188.22) \times S_{UPFC})] \times 1000, \tag{21}$$

where S_{FACTS} is the operating range of the FACTS devices in MVA. In this paper, a five-year period is applied to evaluate the cost function, since the FACTS devices will be in-service for many years.

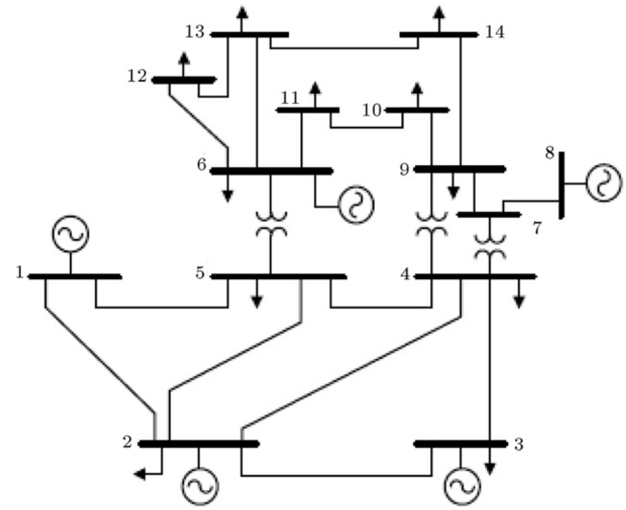

Figure 5: Standard IEEE 14-bus test system.

4. Case studies

During more than 99% of operating time, the focus of the control system is on loss minimization [19]. Thus, in this algorithm, the OPF with active power losses will be undertaken without any FACTS in the system. Then, in the contingent states, FACTS will be added to the network and its best location will be specified, based on the objective function, using the power flow. The objective function is chosen to minimize the average loadability of all energy transmission lines. The OPF and PF problems are implemented in MATLAB, which is linked with GAMS, and which handles nonlinear programming using a CONOPT solver to solve it. The IEEE 14- and 30-bus test cases [20] are considered for this problem. For each contingency, in these cases, average loadability before FACTS, average loadability after optimal location of FACTS, best location and the investment costs of FACTS are determined. In addition, the execution time of the best place to install FACTS for each contingency is specified. Finally, the energy transmission lines are ranked according to the severity of the contingency. The ranking of the contingencies is done according to their calculated objective functions. Also, average loadability, after the fixed location of FACTS and the investment cost of FACTS, is determined. The flowchart of the proposed algorithm is depicted in Figure 4.

4.1. IEEE 14-bus test system

The contingency analysis results for each line outage with OUPFC/UPFC devices in an IEEE 14-bus test system are shown in Table 1. Figure 5 shows the single line diagram of the IEEE 14-bus test system. FACTS devices would reduce the average loadability of energy transmission lines under a single line contingency. In the contingency rankings, line outage 7–9 is ranked as first, which shows the highest average loadability on all energy transmission lines. Results show that the investment cost for OUPFC is far less than UPFC, and the execution time for the optimal location of OUPFC is more than UPFC. Optimal location of OUPFC and UPFC after OPF with minimum active power losses is line 2–4. All lines except line 2–4 are disconnected and results will be achieved with respect to the fixed location OUPFC and UPFC. With regard to these elements in a fixed location, average loadability will be reduced for some

Table 1: Results of each line outage with FACTS devices in IEEE 14-bus test system.

Line outage	Average loadability before FACTS	Average loadability after optimal location OUPFC/UPFC	Optimal location of OUPFC/UPFC	OUPFC/UPFC size (MVA)	OUPFC/UPFC investment cost ($/h)	Execution time (s)	Average loadability after fixed location OUPFC/UPFC	OUPFC/UPFC size (MVA)	OUPFC/UPFC investment cost ($/h)	Rank
7–9	0.2811	0.2764	6–13	20.86	8.26	6.03	0.2908	8.16	3.19	1
		0.2764	6–13	20.86	87.03	5.61	0.2908	8.16	34.66	
6–13	0.2394	0.2307	9–14	19.80	17.32	4.30	0.2381	7.38	6.42	2
		0.2328	1–5	39.73	161.47	4.09	0.2337	5.30	22.61	
9–14	0.2344	0.2274	13–14	11.47	10.05	4.20	0.2394	11.99	3.77	3
		0.2281	4–5	19.84	82.88	4.03	0.2420	5.32	22.67	
2–3	0.2313	0.2232	2–4	52.97	38.29	5.05	0.2232	52.97	38.29	4
		0.2283	3–4	25.83	107.01	4.44	0.2324	5.31	22.64	
6–11	0.2278	0.2208	6–13	20.73	18.12	5.02	0.2272	16.57	12.79	5
		0.2237	2–3	21.73	90.54	4.45	0.2240	5.30	22.61	
4–5	0.2267	0.2153	2–3	20.74	18.13	4.59	0.2215	37.37	32.27	6
		0.2215	2–3	37.44	152.63	4.12	0.2229	5.31	22.65	
6–12	0.2256	0.2209	6–13	21.64	18.92	4.41	0.2277	11.46	6.21	7
		0.2218	2–3	21.59	90.00	4.16	0.2246	5.31	22.64	
4–7	0.2244	0.2214	1–5	42.64	29.49	4.55	0.2229	24.16	20.20	8
		0.2214	1–5	42.64	172.59	4.33	0.2238	5.31	22.64	
5–6	0.2236	0.2151	1–5	28.94	25.27	4.38	0.2161	10.56	9.25	9
		0.2170	2–4	5.34	22.77	4.25	0.2170	5.34	22.77	
2–4	0.2228	0.2201	2–3	26.16	22.86	5.25	–	–	–	10
		0.2201	2–3	26.24	108.63	4.62	–	–	–	
13–14	0.2224	0.2127	9–14	20.33	17.78	4.94	0.2193	18.75	16.40	11
		0.2159	2–3	22.69	94.42	4.11	0.2168	5.30	22.62	
2–5	0.2209	0.2211	6–13	12.61	9.68	5.48	0.2215	22.18	12.58	12
		0.2211	6–13	12.61	53.23	4.52	0.2218	5.29	22.56	
10–11	0.2193	0.2146	6–13	20.13	17.61	4.88	0.2188	15.12	8.55	13
		0.2155	2–3	21.40	89.22	4.33	0.2177	5.31	22.63	
12–13	0.2189	0.2146	2–3	21.85	19.10	4.42	0.2156	14.27	12.49	14
		0.2151	2–3	21.49	89.58	4.19	0.2183	5.31	22.64	
3–4	0.2181	0.2176	2–3	24.22	21.14	4.33	0.2186	20.03	16.39	15
		0.2176	2–3	24.29	100.85	4.15	0.2196	5.29	22.57	
1–2	0.2162	0.2140	4–5	45.48	16.57	4.33	0.2167	13.77	11.56	16
		0.2140	4–5	45.48	183.36	4.09	0.2197	5.31	22.64	
4–9	0.2159	0.2131	4–5	14.93	5.05	4.61	0.2183	18.00	15.75	17
		0.2148	1–5	40.69	165.13	4.36	0.2156	5.31	22.66	
1–5	0.2152	0.2137	2–3	28.86	25.21	4.19	0.2300	55.18	48.00	18
		0.2300	2–4	55.18	219.56	3.97	0.2300	55.18	219.56	
9–10	0.2143	0.2227	9–14	21.92	9.67	4.25	0.2251	14.17	8.58	19
		0.2258	1–5	42.09	170.48	4.06	0.2277	5.31	22.67	

contingencies. In both cases of optimal and fixed locations, in some contingencies, adding FACTS will increase average loadability, which shows that the elements used for these contingencies would not be effective.

4.2. IEEE 30-bus test system

The results of the single line contingency with OUPFC and UPFC devices in an IEEE 30-bus test system are presented in Table 2. Figure 6 depicts the single line diagram of the IEEE 30-bus test system. In the test system, FACTS devices would reduce average loadability on all energy transmission lines under a single line contingency. In contingency ranking, line outage 28–27 is ranked as the most severe, which shows the highest average loadability on all energy transmission lines. Also, results in the IEEE 30-bus test system show that the investment cost for OUPFC is far less than UPFC, and that execution time for the optimal location of OUPFC is more than UPFC. Optimal location of OUPFC and UPFC after OPF with minimal active power losses is line 2–5. All lines except line 2–5 are disconnected and results will be achieved with respect to the fixed location OUPFC and UPFC. Note that, in this case, the optimal location of FACTS devices in most contingencies is line 2–5. Thus, line 2–5 can be considered as the fixed location of FACTS devices.

5. Conclusions

Under emergency conditions, FACTS devices can be implemented to enhance system security. In this paper, the optimal

Table 2: Results of each line outage with FACTS devices in IEEE 30-bus test system.

Line outage	Average loadability before FACTS	Average loadability after optimal location OUPFC/UPFC	Optimal location of OUPFC/UPFC	OUPFC/UPFC size (MVA)	OUPFC/UPFC investment cost ($/h)	Execution time (s)	Average loadability after fixed location OUPFC/UPFC	OUPFC/UPFC size (MVA)	OUPFC/UPFC investment cost ($/h)	Rank
28–27	0.4072	0.3984	2–5	64.40	55.94	14.28	0.3984	64.40	55.94	1
		0.3984	2–5	64.40	253.10	12.72	0.3984	64.40	253.10	
9–10	0.3661	0.3625	2–5	47.04	22.67	11.47	0.3625	47.04	22.67	2
		0.3605	2–5	30.57	125.83	10.97	0.3605	30.57	125.83	
2–5	0.3497	0.3354	2–6	81.79	70.85	11.05	–	–	–	3
		0.3485	5–7	27.51	113.69	10.34	–	–	–	
12–15	0.3344	0.3339	2–6	46.73	17.30	11.09	0.3370	42.34	22.36	4
		0.3302	2–5	20.19	84.32	10.42	0.3302	20.19	84.32	
10–20	0.3270	0.3173	2–5	65.22	51.33	15.41	0.3173	65.22	51.33	5
		0.3173	2–5	65.22	256.02	13.27	0.3173	65.22	256.02	
10–21	0.3256	0.3221	2–5	48.50	37.73	11.72	0.3221	48.50	37.73	6
		0.3195	2–5	33.62	137.79	10.97	0.3195	33.62	137.79	
27–30	0.3238	0.3208	2–5	48.77	42.46	11.44	0.3208	48.77	42.46	7
		0.3176	2–5	33.79	138.46	10.39	0.3176	33.79	138.46	
4–6	0.3234	0.3036	2–6	82.33	71.31	14.39	0.3161	46.11	40.16	8
		0.3054	2–5	91.66	347.53	12.31	0.3054	91.66	347.53	
12–16	0.3223	0.3173	2–5	48.94	25.68	11.50	0.3173	48.94	25.68	9
		0.3155	2–5	35.43	144.83	10.39	0.3155	35.43	144.83	
15–23	0.3197	0.3154	2–5	48.46	24.87	11.58	0.3154	48.46	24.87	10
		0.3132	2–5	34.21	140.07	10.30	0.3132	34.21	140.07	
19–20	0.3194	0.3097	2–5	65.44	51.62	13.72	0.3097	65.44	51.62	11
		0.3097	2–5	65.44	256.82	12.25	0.3097	65.44	256.82	
1–2	0.3176	0.3133	1–3	38.98	33.99	10.55	0.3140	24.07	21.04	12
		0.3092	2–5	43.75	176.80	10.39	0.3092	43.75	176.80	
6–28	0.3165	0.3167	2–6	48.14	26.93	11.22	0.3186	44.13	38.45	13
		0.3138	2–5	18.70	78.23	10.45	0.3138	18.70	78.23	
12–14	0.3160	0.3113	2–5	50.19	40.66	11.83	0.3113	50.19	40.66	14
		0.3096	2–5	33.72	138.19	10.62	0.3096	33.72	138.19	
15–18	0.3138	0.3106	2–5	48.88	42.55	11.58	0.3106	48.88	42.55	15
		0.3075	2–5	34.14	139.82	10.41	0.3075	34.14	139.82	
25–27	0.3138	0.3048	2–5	65.14	51.25	14.95	0.3048	65.14	51.25	16
		0.3048	2–5	65.14	255.74	11.59	0.3048	65.14	255.74	
2–6	0.3132	0.3111	2–5	52.32	29.54	10.92	0.3111	52.32	29.54	17
		0.3111	2–5	52.32	208.98	10.20	0.3111	52.32	208.98	
22–24	0.3131	0.3088	2–5	50.09	40.75	11.88	0.3088	50.09	40.75	18
		0.3070	2–5	33.51	137.36	10.84	0.3070	33.51	137.36	
10–22	0.3128	0.3060	2–5	36.09	20.91	12.58	0.3060	36.09	20.91	19
		0.3060	2–5	36.09	147.40	11.81	0.3060	36.09	147.40	
8–28	0.3122	0.3081	2–5	49.77	40.26	10.84	0.3081	49.77	40.26	20
		0.3060	2–5	33.55	137.51	10.30	0.3060	33.55	137.51	
10–17	0.3121	0.3024	2–5	65.65	51.90	14.70	0.3024	65.65	51.90	21
		0.3024	2–5	65.65	257.57	12.24	0.3024	65.65	257.57	
3–4	0.3119	0.3046	2–5	64.04	55.61	11.27	0.3046	64.04	55.61	22
		0.3034	2–5	58.90	233.17	10.91	0.3034	58.90	233.17	
6–10	0.3108	0.3009	2–5	65.78	52.10	14.84	0.3009	65.78	52.10	23
		0.3009	2–5	65.78	258.02	12.53	0.3009	65.78	258.02	
27–29	0.3100	0.3055	2–5	50.23	41.42	11.80	0.3055	50.23	41.42	24
		0.3040	2–5	33.70	138.11	10.86	0.3040	33.70	138.11	
16–17	0.3098	0.3054	2–5	50.96	40.76	11.39	0.3054	50.96	40.76	25
		0.3032	2–5	35.03	143.29	10.50	0.3032	35.03	143.29	
21–22	0.3089	0.2990	2–5	66.17	52.55	13.28	0.2990	66.17	52.55	26
		0.2990	2–5	66.17	259.43	11.61	0.2990	66.17	259.43	

(continued on next page)

Table 2 (*continued*)

Line outage	Average loadability before FACTS	Average loadability after optimal location OUPFC/UPFC	Optimal location of OUPFC/UPFC	OUPFC/UPFC size (MVA)	OUPFC/UPFC investment cost ($/h)	Execution time (s)	Average loadability after fixed location OUPFC/UPFC	OUPFC/UPFC size (MVA)	OUPFC/UPFC investment cost ($/h)	Rank
23–24	0.3087	0.3042	2–5	50.10	41.53	11.78	0.3042	50.10	41.53	27
		0.3023	2–5	33.78	138.41	10.94	0.3023	33.78	138.41	
6–9	0.3081	0.2984	2–5	65.75	51.97	14.23	0.2984	65.75	51.97	28
		0.2984	2–5	65.75	257.93	11.47	0.2984	65.75	257.93	
14–15	0.3069	0.2976	2–5	55.25	40.21	12.20	0.2976	55.25	40.21	29
		0.2976	2–5	55.25	219.81	10.97	0.2976	55.25	219.81	
18–19	0.3065	0.3017	2–5	47.37	24.58	11.97	0.3017	47.37	24.58	30
		0.3002	2–5	33.93	139.00	10.64	0.3002	33.93	139.00	
24–25	0.3054	0.2963	2–5	65.38	51.54	13.24	0.2963	65.38	51.54	31
		0.2963	2–5	65.38	256.58	11.00	0.2963	65.38	256.58	
29–30	0.3053	0.3007	2–5	47.17	24.33	12.39	0.3007	47.17	24.33	32
		0.2991	2–5	33.61	137.76	10.92	0.2991	33.61	137.76	
5–7	0.3044	0.3006	2–6	49.33	37.47	11.45	0.3059	10.92	4.01	33
		0.3051	10–21	16.17	67.89	10.26	0.3062	21.32	88.90	
6–8	0.3040	0.2935	2–5	68.20	55.09	15.59	0.2935	68.20	55.09	34
		0.2935	2–5	68.20	266.66	12.98	0.2935	68.20	266.66	
1–3	0.3035	0.3068	12–15	34.51	16.32	11.05	0.3336	48.23	41.99	35
		0.2653	10–22	23.04	95.82	10.19	0.3177	5.05	21.55	
2–4	0.3035	0.3028	2–5	56.44	29.97	10.98	0.3028	56.44	29.97	36
		0.3002	2–5	38.51	156.78	10.39	0.3002	38.51	156.78	
6–7	0.2988	0.3007	2-5	72.43	62.81	10.98	0.3007	72.43	62.81	37
		0.3007	2–5	72.43	281.61	10.61	0.3007	72.43	281.61	
4–12	0.2927	0.3018	10–21	41.80	15.96	11.02	0.3093	42.35	36.49	38
		0.2813	27–30	1.34	5.74	10.45	0.3131	5.05	21.55	

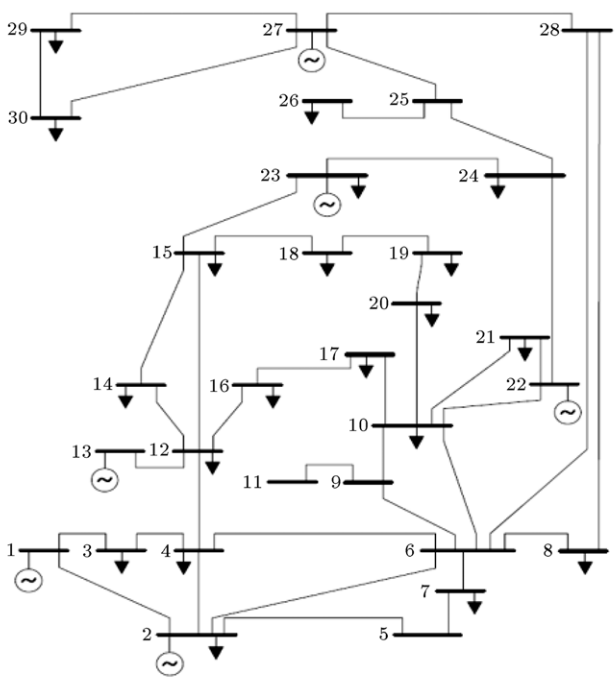

Figure 6: Standard IEEE 30-bus test system.

location of FACTS devices is performed to minimize average loadability on all energy transmission lines subject to different single-line contingency states, while satisfying the operational constraints of the power system. Case studies have been implemented using IEEE 14- and 30-bus test systems. Results indicate the efficiency of the framework in enhancing the security of the energy supply under a single line contingency. Also, simulation results show that implementation of the OUPFC and UPFC performance is approximately the same, while OUPFC investment cost is much less than that of UPFC, with the cost of higher computational burden. Eventually, it is noted that the proposed scheme for the placement of the FACTS devices is well-suited for weak power systems that are almost in contingent situations.

Appendix A

A.1. OUPFC data

$$-20^\circ \le \sigma \le 20^\circ; \quad 0 \le r \le 0.15; \quad -\pi \le \gamma \le \pi;$$
$$X_B = 0.007 \text{ p.u.}; \quad X_E = 0.001 \text{ p.u.}; \quad S_{base} = 100 \text{ MVA};$$
$$S_{OUPFC} \le S_{OUPFC}^{\max}; \quad S_{OUPFC}^{\max} = 100 \text{ MVA}.$$

A.2. UPFC data

$$0 \le r \le 1; \quad X_B = 0.007 \text{ p.u.}; \quad X_E = 0.001 \text{ p.u.};$$
$$-\pi \le \gamma \le \pi; \quad S_{base} = 100 \text{ MVA}; \quad S_{UPFC} \le S_{UPFC}^{\max};$$
$$S_{UPFC}^{\max} = 100 \text{ MVA}.$$

References

[1] Gyugyi, L., *A Unified Power Flow Control Concept for Flexible AC Transmission Systems*, pp. 19–25, Westinghouse Electric Corporation, USA (1991).

[2] Lashkar Ara, A., Kazemi, A. and Nabavi Niaki, S.A. "Modelling of Optimal Unified Power Flow Controller (OUPFC) for ptimal steady-state performance of power systems", *Energy Convers. Manage.*, 52(2), pp. 1325–1333 (2011).

[3] Shao, W. and Vittal, V. "LP-based OPF for corrective FACTS control to relieve overloads and voltage violations", *IEEE Trans. Power Syst.*, 21(4), pp. 1832–1839 (2006).

[4] Rashed, G.I., Shaheen, H.I., Duan, X.Z. and Cheng, S.J. "Evolutionary optimization techniques for optimal location and parameter setting of TCSC under single line contingency", *Appl. Math. Comput.*, 205(1), pp. 133–147 (2008).

[5] Visakha, K., Thukaram, D. and Jenkins, L. "Application of UPFC for system security improvement under normal and network contingencies", *Electr. Power Syst. Res.*, 70(1), pp. 46–55 (2004).

[6] Etemad, R., Navabi, R. and Shayanfar, H.A. "Optimal location and setting of TCSC under single line contingency using mixed integer nonlinear programming", *Proceedings of 9th International Conference on Environment and Electrical Engineering*, EEEIC, Tehran, Iran, pp. 250–253 (2010).

[7] Lu, Y. and Abur, A. "Improving system static security via optimal placement of thyristor controlled series capacitors (TCSC)", *Proceedings of IEEE Power Engineering Society Winter Meeting*, Ohio, USA, pp. 516–521 (2001).

[8] Joorabian, M., Larki, F., Kelk, H.M., Pishvaei, M. and Johar, A. "Optimal location of STATCOM and SVC based on contingency voltage stability by using continuation power flow: case studies of Khouzestan power networks in Iran", *Proceedings of IEEE International Conference on Computer and Electrical Engineering*, Dubai, UAE, pp. 179–183 (2009).

[9] Lashkar Ara, A., Kazemi, A. and Nabavi Niaki, S.A. "Multiobjective optimal location of FACTS shunt-series controllers for power system operation planning", *IEEE Trans. Power Deliv.*, 27(2), pp. 481–490 (2012).

[10] Lashkar Ara, A., Kazemi, A. and Behshad, M. "Improving power systems operation through multiobjective optimal location of optimal unified power flow controller", *Turk. J. Electr. Eng. Comput. Sci.* (2012) (http://dx.doi.org/10.3906/elk-1203-40).

[11] General Algebraic Modeling System (GAMS). http://www.gams.com (accessed 27.10.2010).

[12] Mete Vural, A. and Tumay, M. "Mathematical modeling and analysis of a unified power flow controller: a comparison of two approaches in power flow studies and effects of UPFC location", *Electr. Power Energy Syst.*, 29(8), pp. 617–629 (2007).

[13] Nabavi Niaki, S.A. "A novel steady-state model and principles of operation of phase-shifting transformer comparable with FACTS new devices" *Proceedings of IEEE International Conference on Power System Technology*, POWERCON, Kunming, China, pp. 1450–1457 (2002).

[14] Noroozian, M., Angquist, L., Ghandhari, M. and Andersson, G. "Use of UPFC for optimal power flow control", *IEEE Trans. Power Deliv.*, 12(4), pp. 1629–1634 (1997).

[15] Lashkar Ara, A., Kazemi, A., Gahramani, S. and Behshad, M. "Optimal reactive power flow using multi-objective mathematical programming", *Sci. Iranica Trans. D: Comput. Sci. Eng. Electr. Eng.*, 19(6), pp. 1829–1836 (2012).

[16] Rezaeipour, R., Kazemi, A. and Lashkar Ara, A. "Optimal location of Rotary Hybrid Flow Controller (RHFC) through multi-objective mathematical programming", *Sci. Iranica Trans. D: Comput. Sci. Eng. Electr. Eng.*, 19(6), pp. 1771–1779 (2012).

[17] Saravanan, M., Slochanal, S.M.R., Venkatesh, P. and Abraham, J.P.S. "Application of particle swarm optimization technique for optimal location of FACTS devices considering cost of installation and system loadability", *Electr. Power Syst. Res.*, 77(3–4), pp. 276–283 (2007).

[18] Cai, L.J. and Erlich, I. "Optimal choice and allocation of FACTS devices using genetic algorithm", *Proceedings on Twelfth Intelligent Systems Application to Power Systems Conference*, Lemnos, Greece, pp. 1–6 (2003).

[19] Grunbaum, R., Lundberg, P., Stromberg, G. and Berggren, B. "Congestion relief: FACTS—the key to congestion relief", *ABB Rev.*, 2, pp. 28–32 (2007).

[20] Power systems test case archive. http://www.ee.washington.edu/research/pstca (accessed 21.01.2008).

Afshin Lashkar Ara was born in Tehran, Iran, in 1973. He received a B.S. degree from the Islamic Azad University, Dezful Branch, Iran, in 1995, an M.S. degree from the University of Mazandaran, Babol, Iran, in 2001, and a Ph.D. degree from Iran University of Science and Technology (IUST), Tehran, Iran, in 2011, all in Electrical Engineering. He is currently Faculty Member of the Islamic Azad University, Dezful Branch, Iran, as well as member of the IEEE Power and Energy Society (IEEE-PES). His current research interests include: analysis, operation and control of power systems, and FACTS controllers.

Jamshid Aghaei received B.S., M.S. and Ph.D. degrees in Electrical Engineering from Iran University of Science and Technology (IUST), Tehran, Iran, in 2003, 2005 and 2009, respectively. His research interests are in the application of FACTS devices and power markets, power system operation and restructuring and application of optimization in power system studies. He is a member of IEEE.

Mohammad Alaleh was born in Dezful, Iran, in 1986. He received B.S. and M.S. degrees in Electrical Engineering from the Islamic Azad University, Dezful Branch, Iran, in 2008 and 2011, respectively. His research interests include: power system analysis, and FACTS devices.

Hassan Barati was born in Dezful, Iran, in 1973. He received a B.S. degree from Isfahan University of Technology, Iran, in 1994, an M.S. degree from Tabriz University, Iran, in 1997, and a Ph.D. degree from the Islamic Azad University, Science and Research Branch, Tehran, Iran, in 2007, all in Electrical Engineering. His research interests include: power system analysis, restructured power system, and FACTS devices.